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STUDIES OF THE INITIATION OF ELECTRICAL BREAKDOWN IN VACUUM

R. P. Little and W. T. Whitney

Electron Tubes Branch
Electronics Division

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NAVAL RESEARCH LABORATORY
Washington, D.C.

ABSTRACT

It is generally known that an applied field of 10^5 v/cm will produce electron emission from apparently smooth surfaces at room temperature. This prebreakdown current is believed to initiate electrical breakdown in vacuum. Experimentally is has been found that this prebreakdown emission is independent of emitter temperature up to 800°C. By using electron-shadow-microscope techniques, projections about two microns high, capable of producing field enhancements of the order of 100, have been found on optically polished cathodes at prebreakdown emission sites. This, with other evidence, strongly indicates that prebreakdown emission is Fowler-Nordheim field emission, due to geometrical field enhancement.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

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STUDIES OF THE INITIATION OF ELECTRICAL BREAKDOWN IN VACUUM

INTRODUCTION

Electrical breakdown in vacuum imposes design limitations on a surprising variety of electronic and vacuum devices. Among these are vacuum capacitors, rectifier and modulator tubes, electrostatically focused traveling-wave tubes, control electrodes in high-power electron guns, electrostatic lenses in electron microscopes, and electrostatically suspended frictionless bearings.

It is generally known that in vacuum an applied electric field of 10^5 v/cm will produce electron emission from apparently smooth surfaces at room temperature. This electron emission usually precedes electrical breakdown, and this prebreakdown current is believed to be an initiating mechanism for electrical breakdown across small gaps in vacuum (1).

According to the Fowler-Nordheim field-emission theory (1), for usual work functions, electric fields on the order of 10^7 v/cm are required to obtain field-emitted electrons. Alternatively, the Richardson-Schottky equation (1) requires a work function of a few tenths of an electron volt to obtain thermionic emission at room temperature.

This report presents the results of some experimental tests on prebreakdown currents which show that prebreakdown emission is neither thermionic nor photoelectric, and which clearly indicate that prebreakdown emission is field emission from field-enhancing needle-like projections on the cathode surface.

A discussion of several attempts to delay the onset of prebreakdown current by special treatment of the cathode surface is included in Appendix A.

EXPERIMENTAL TUBE

The test device used in these experiments is a simple diode having a two-inch-diameter anode disk of polished Vycor glass on which has been deposited a transparent conducting film of zinc silicate phosphor (2). The resulting anode is about 95 percent transparent to white light, provides a high-resolution fluorescence when bombarded by electrons, and offers a resistance to emission current of about 1000 ohms. The one-half-inch-diameter metal cathode has Rogowski-shaped (3) edges to prevent field enhancement. Incorporated in the cathode assembly is a heater and thermocouple to permit temperature measurements. The cathode-anode spacing (breakdown gap) is maintained at 0.015 ± 0.0005 inch by means of mounting rods of insulating fused glass. Standard cleaning and processing procedures are used during fabrication, and the assemblies are tested in an ion-pumped oil-free vacuum better than 10^{-7} torr.

When the anode potential on a test tube is increased to approximately 7 kv, a current of about 10^{-9} ampere starts to flow. Simultaneously, there appear one or more tiny fluorescent images on the anode. These emission spots have the following characteristics: they are reproducible, in that if the electric field is removed and applied again at a later time, the images reappear at the same locations (provided there is no discharge or breakdown to change the cathode emitting surfaces) and they are unchanged in size and location when equal peak values of either direct, 60-cycle, or 300-kc voltages are applied.

All of the images are very small, with diameters of 0.2 mm or less. When the electric field is reversed, making the cathode positive, the fluorescence is not visible; this suggests that the current is chiefly electron flow.

Current-voltage data have been taken on many of these tubes, which have had cathodes constructed of different metals (including type 304 stainless steel, single-crystal tungsten, nickel, tantalum, OFHC copper, type 6061 aluminum, and magnesium) with different degrees of finish (e.g., machined, optically polished, electropolished). In each test, when the number of emission spots remained constant (total emission area constant), the data agree qualitatively with the Fowler-Nordheim equation. To obtain quantitative agreement, either an extremely low work function (e.g., 0.3 ev) or a large field enhancement (e.g., 100) at the cathode surface must be assumed.

LOW WORK FUNCTION

Temperature Dependence

The presence of an extremely low work function (a few tenths of an electron volt) is indicated by the Fowler-Nordheim equation if prebreakdown emission is assumed to be field emission without a local field enhancement. Similarly, an extremely low work function is indicated by the Richardson-Schottky equation, if prebreakdown emission is assumed to be thermionic.

The assumption of such a low work function would predict an easily observable temperature dependence of the emission even at room temperature. To investigate this, tests were run by varying the cathode temperature while simultaneously monitoring the current from a single emission area by means of a photomultiplier tube. Figure 1 is a block-diagram illustration of the equipment used. The light output from a single emission spot on the phosphor-coated anode was collected by means of a 300X optical microscope onto the cathode of a photomultiplier tube. The output of this tube was fed through a linear amplifier and into a sensitive recorder. The detector was calibrated to read prebreakdown current, which was found to be proportional to the light intensity of the phosphor in the range of operation. It is necessary to isolate and measure the current

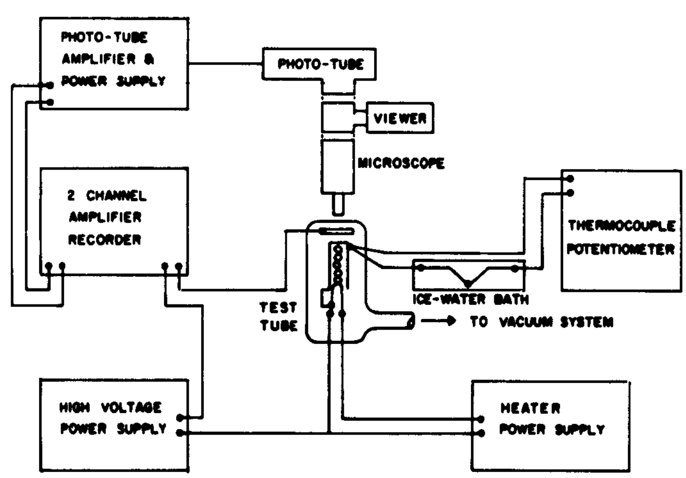


Fig. 1 - Block diagram of the apparatus for measuring the temperature dependence of prebreakdown emission

of a single emission site, since each site probably has different emission constants. To eliminate the effects of changes in separation of the electrodes due to thermal expansion, the gap spacing was checked periodically, by optical means, and the applied voltage was adjusted to maintain the gross electric field constant. It was found that the magnitude of the prebreakdown current from a stainless steel cathode remained fairly constant (within 30 percent) from -196°C to 750°C. Similar results were obtained from a single-crystal tungsten cathode until a temperature of 800°C was reached. At this temperature the total tube current started to rise exponentially (Fig. 2), indicating the onset of thermionic emission.

It is, therefore, shown that at temperatures below 800°C prebreakdown emission is not thermally dependent (or is not thermionic emission).

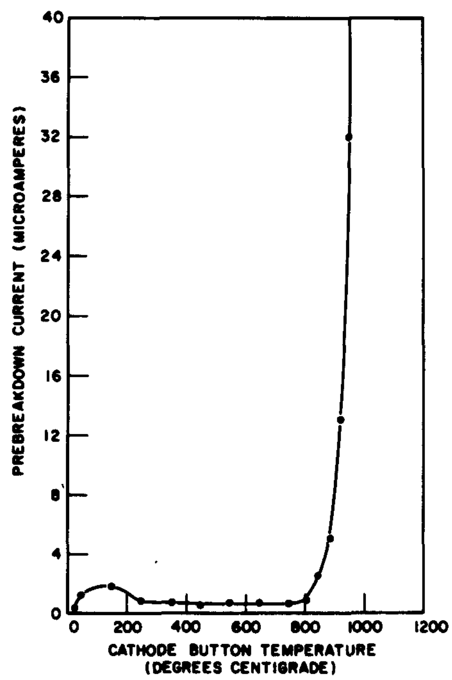


Fig. 2 - Prebreakdown current vs temperature of a tungsten cathode button under the influence of a constant electric field of 10^5 v/cm

Photoelectric Effect

Associated with a low-work-function cathode is the phenomenon of photoelectric emission. However, it was found that when the cathode was illuminated with white light, there was no observable increase in the prebreakdown emission, except when the cathode had been intentionally contaminated with cesium or barium.

Effects of Low-Work-Function Contaminants

The number and location of prebreakdown spots produced by a certain applied electric field were recorded by photographing the entire cathode surface through a 10X microscope. Then cesium was evaporated onto the cathode sleeve and allowed to migrate over the emission surface. When the migration was complete, the same initial prebreakdown mission spots could be obtained at only one-third the applied field needed before cesium contamination. Corresponding tests with barium contamination indicated that about one-half the original field was required to obtain initial emission spots.

It was especially noted that the prebreakdown emission fluorescent images were in exactly the same locations before, during, and after cesium or barium contamination (the contaminant was removed by heating the cathode). Such results indicate that the contaminant substantially aided the residual emission mechanism at each emitting site. An assumption that the emitting sites are field-enhancing projections of the parent cathode metal is consistent with the above observations.

FIELD ENHANCEMENT FROM A MICROPROJECTION

It should be noted that before 1940 a similar inconsistency between theory and experiment was encountered by investigators studying field emission from points. Using an electron microscope to examine his tungsten points, Haefer (4) found small projections on them. He determined that the field enhancement (about ten) produced by these projections was sufficient to give quantitative agreement between the Fowler-Nordheim theory and experiment.

Light-Microscopy Experiments

If a field-enhancing projection were present on the cathode surface, one might expect that it could be seen optically with a relatively high-power microscope. Observations of a prebreakdown emission site, in situ, through the transparent anode by means of a 300X microscope (Fig. 3) reveals an irregularity present on only about 80 percent of the sites observed. The size of the irregularity is too small at this power to determine what magnitude of field enhancement it should produce.

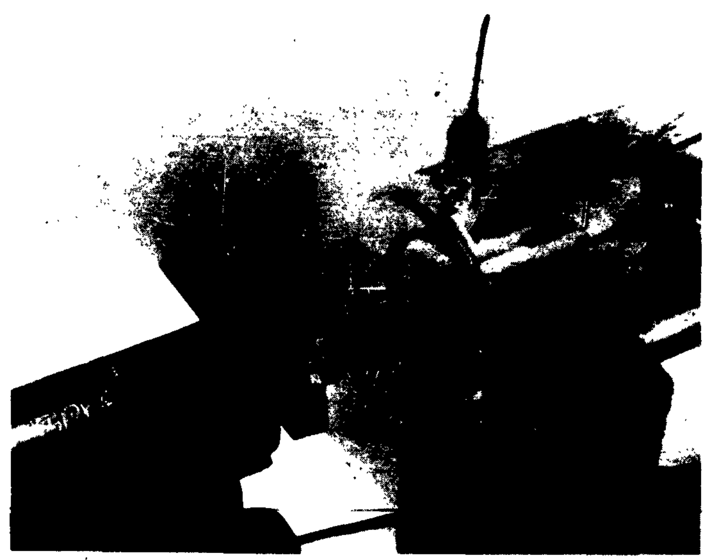


Fig. 3 - The microscope in position for viewing the cathode through the tube envelope and transparent anode

Incandescent Emitting Site

On a polished tungsten cathode, several emission sites have been observed, through a 300X microscope, to incandesce when the gross cathode temperature is at least 500°C, and if the prebreakdown current is large (no incandescence can be seen at room temperature even with high current). This phenomenon can be observed even when a surface irregularity is not visible by reflected light. The diameter of the incandescent spot is less than 5 microns. Using this, the anode-image diameter, and the anode-cathode spacing, the angular spread of the electron beam is calculated to be about 30 degrees. The field enhancement of a projection could cause this spread.

This incandescence phenomenon implies that a thin projection, or whisker, is being resistively heated (5). However, calculations to prove this are inconclusive, in this case, since the current density is not sufficiently well determined.

"Hair-Raising" Effect

In some tests (using a high-impedance power supply to prevent large surges of current) when the dc field on a virgin cathode was slowly increased, a bright emission spot suddenly appeared. Then the gross field could be decreased to almost half of this critical value before the emission spot disappeared. The spot usually reappeared at the same gross field at which it disappeared. It is conceivable that the electrostatic force due to the applied field could swing projections, or whiskers, out from the surface of a cathode. Thus, a field-enhancing projection could be elevated from the cathode surface and remain so after the raising force was removed.

Electron-Shadow-Microscope Investigation

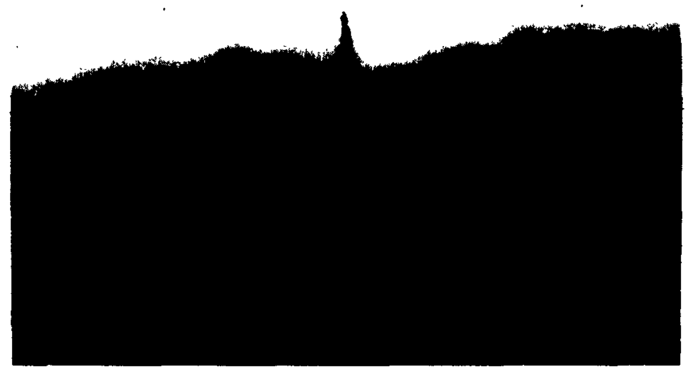
The use of an electron-shadow microscope has proven more advantageous to the study than a high-power transmission electron microscope. Transmission electron-microscope observations (12,000X) of emitting sites on four different cathodes failed to reveal the presence of any sharp projections which might produce a field enhancement of 100. (No whiskers were found.) But since replica techniques were used, and since the emitting sites could not be examined in situ, this result is not conclusive.

In preparing for electron-shadow-microscopy, prebreakdown emission sites were observed on several optically polished cathodes by viewing through the anode with a light microscope, as previously mentioned. By various measurements to known marks and scratches, these emission sites have been located within an area of approximately 0.25 mm^2 on the cathode surface, this area size being determined by the probable measurement errors. These cathodes have been transferred from the oil-free vacuum system to the electron-shadow-microscope, RCA Type EMD-2. Within the designated areas, in all of the 50 units tested, needle-like projections have been observed. The projections are typically two microns in height (although some are as small as 0.5 micron) and have a height-to-base-diameter ratio of about ten. Figure 4a shows a projection on the surface of an optically polished type 304 stainless steel cathode, and Fig. 4b a similar projection on an optically polished type 6061 aluminum cathode.

Installing a diode structure inside the electron-shadow-microscope housing with the cathode button held in the microscope specimen holder made it possible to apply the diode electric field and obtain prebreakdown emission sites on the cathode opposite the transparent anode as before. By means of the microscope stage adjustments, the cathode was then properly oriented for a shadow picture of the emission site. This arrangement eliminated the necessity for transporting the specimen from one test system to another. All of the emission sites observed in this manner revealed cathode-surface projections similar to those shown in Fig. 4. Copper, stainless steel, aluminum, silver, and columbium cathodes were used in these experiments.

Actual observations of "hair-raising" instances have been observed with the electron-shadow microscope. The surface of a virgin cathode has been carefully examined for such projections before being subjected to the force of an electrostatic field, without any whiskers having been found. After obtaining prebreakdown emission from this same surface, a projection has been observed by the shadow method.

A prolate hemispheroid on a flat surface with a height-to-base-diameter ratio of eight will produce a field enhancement of 100. Since the projections at the emission



(a) 304 stainless steel

(b) Aluminum

Fig. 4 - Microprojections in the emission areas on optically polished cathode surfaces, magnification approximately 1000X

sites have approximately these dimensions, it is concluded that the observed projections can provide the necessary enhancement to produce field-emitted electrons at gross fields of 10^5 v/cm.

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Appendix A

ATTEMPTS TO SUPPRESS PREBREAKDOWN EMISSION

According to several theories,* field emission from the cathode is the initiating mechanism for electrical breakdown in vacuum. Numerous approaches have been tried to suppress this initiating emission in an attempt to delay electrical breakdown in vacuum to higher gross fields.

The investigations started by testing surfaces which were polished to remove foreign matter and provide a planar surface. Optical grinding and polishing increased the first emission voltage by a factor of two over a machine finish, while electropolishing proved less effective. Considering recent findings, reported in the main body of this paper, and assuming the emitting sites are minute projections of the order of 0.5 micron tall, it should not be expected that ordinary polishing techniques would reduce such geometries significantly.

Attempts were made to use the heat-treatment techniques of field-emission microscopy for removing these surface anomalies. In such a system the emitter point is heated to a temperature where surface migration of the metal takes place, thus smoothing off all projections. A polished tungsten cathode button was radio-frequency heated to more than 2200°C in a vacuum of 10^{-4} torr for about fifteen minutes. It was then incorporated in an experimental tube, where it was heated to 1200°C in a vacuum of 10^{-7} torr for several days. Neither of these heat treatments increased the first emission voltage significantly. Several type 304 stainless steel cathodes have been heated in vacuum until much sublimation has occurred. This also produced little change in first emission voltage.

Glow discharging the cathodes has increased the voltage required to obtain this initiating emission by about a factor of two. Whether the cathode was positive or negative during the discharge, or whether argon, hydrogen, oxygen, or air were used as the discharge gas made little difference.

In an attempt to obtain ultraclean surfaces whose inclusions and projections would be covered over, evaporated layers of platinum, gold, and nickel have been applied. Some improvement was noted with these cathodes, but it could be attributed to the glow discharging necessary before evaporating the metals.

Thin dielectric coatings on the cathode have produced the greatest improvement. Teflon on type 304 stainless steel increases the first emission voltage by a factor of two or three; nylon on type 304 stainless steel and aluminum oxide on type 6061 aluminum gives a factor of four or five. It appears that if the breakdown strength of the dielectric is high, its conductivity not too low, and its adhesion to the cathode metal strong, then the first emission voltage can be increased by at least a factor equal to the dielectric constant of the coating material.

*R. Hawley, "Vacuum as an Insulator," Vacuum 10:314 (1960).

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